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HEAT AND MASS TRANSFER BY HYDROMAGNTIC MIXED CONVECTION FLOW ALONG A VERTICAL CYLINDER EMBEDDED IN A NON-DARCY POROUS MEDIUM WITH HEAT SOURCE

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ABSTRACT

The problem of coupled heat and mass transfer by steady mixed convection flow of an incompressible, viscous and electrically conducting fluid along a vertical cylinder embedded in a non-Darcy porous medium with heat generation will be studied. The problem will be analyzed for the case of variable surface temperature and concentration. The entire region of the mixed convection is involved. The mixed convection parameter varies from pure natural convection to pure forced convection. The partial differential equations will be transformed into the non-similar boundary layer equations, which can be solved numerically by the finite difference method. From the present study, it can be concluded that rise in curvature and buoyancy ratio factors lead to higher heat and mass transfer. Heat and mass transfer drop as the inertia and square of Hartmann number rises. As Lewis number increases, Nussel number drops while Sherwood number rises. Increasing the heat generation parameter leads to lower Nusselt number. Sherwood number doesn't affect when increasing the heat generation parameter.

KEYWORDS: Porous Medium, Mixed Convection, Heat and Mass Transfer, Vertical Cylinder & Heat Source

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Original Article

1. INTRODUCTION

Simultaneous heat and mass transfer from diverse geometries embedded in fluid-saturated porous media have many engineering applications, such as petroleum reservoirs, enhanced oil recovery, thermal insulation, chemical catalytic reactors and processes, nuclear waste disposal, cooling of nuclear reactors and drying of porous solids. This type of flow is driven by buoyancy due to temperature and concentration gradients and fluid flow. It was well known that the Darcy law is valid for slow flows and without the inertia and no-slip boundary effects, along with the assumption of uniform porosity and the neglect of thermal dispersion effects. These non-Darcian flow phenomena change importantly the predictions of temperature and flow fields when compared with that predicted by the Darcy law. Therefore, the involving of non-Darcian effects in the analysis is significant to approximate more closely, the results in the realistic situations.

The study of convection heat / mass transfer and fluid flow over a circular cylinder embedded in saturated porous media has received great attention in previous and recent years. Merkin and Pop [1] considered the problem of the mixed convection boundary layer on a vertical circular cylinder. Kumari et al. [2] presented study deals with the effect of the thermal dispersion on the non-Darcy mixed convection flow on a vertical cylinder. Hooper et al. [3] used Darcy model to analyze the problem of mixed convection from an isothermal vertical cylinder. Aldoss et al. [4] investigated non-Darcy mixed convection flow from a vertical cylinder. Aldoss [5] used non-Darcy model and considered MHD mixed convection flow. Kumari et al. [6] studied numerically using the Darcy law the effect of

steady non-uniform suction or injection on mixed convection boundary layer flow over a vertical heated or cooled permeable slender cylinder. Assisting and opposing flow cases are considered. Mukhopadhyay and Ishak [7] presented an analysis to study the effects of thermal stratification on boundary layer axisymmetric mixed convection flow along a stretching cylinder. Shu et al. [8] studied the problem of steady combined convection flow on a cooled vertical permeable circular cylinder.

In this work, simultaneous heat and mass transfer by steady combined convection flow of an incompressible, viscous and electrically conducting fluid along a vertical cylinder embedded in a non-Darcy porous medium with heat generation will be analyzed.

2. MATHEMATICAL FORMULATION

Consider steady, two dimensional, laminar, simultaneous heat and mass transfer by combined convection flow of fluid along a vertical cylinder embedded in a fluid-saturated porous medium. Figure 1 represent the coordinate system. In order to mathematically analyze the problem, it will be assumed that the gravitational acceleration is acting in the negative x-direction. The fluid is viscous, incompressible, electrically conducting, Newtonian, and has constant properties excluding the density in the buoyancy term of the momentum equation that is approximated according to the Boussinesq approximation. For low permeability and porosity, the viscous resistance due to the solid boundary is small and can, therefore, be neglected. Experimental observations indicate that pressure drop is proportional to a linear collection of flow velocity and the square of it [9]. It will be assumed that the surface temperature and concentration change with the x-direction according to the power law, and constant at the free stream.

Furthermore, surface temperature and concentration are greater than the free stream values. The porous medium is assumed to be non-deformable and the solid matrix is in thermal equilibrium with the fluid filling the pores. With the above assumptions and by introducing the Boussinesq and boundary layer approximations, the governing boundary layer equations are given by

2.1 Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial (rv)}{\partial r} = 0 \qquad (1)$$

where u and v are the velocity components in the x and r directions respectively.

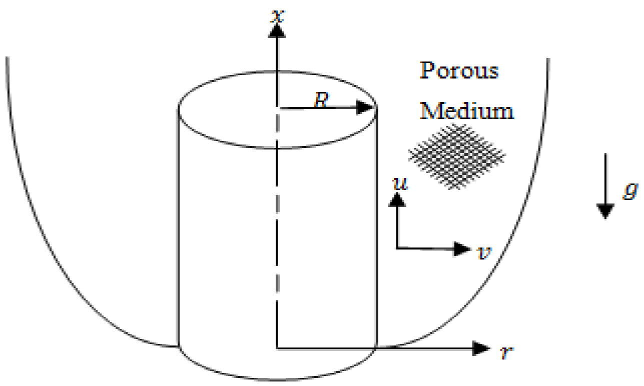

Figure 1: Flow Model and Physical Coordinate.

2.2 Momentum Equation [10, 11]

a. In the x-direction

$$u = -\frac{K}{\mu}\left(\frac{\partial P}{\partial x} + \rho g + \frac{\sigma \beta_0^2 u}{\emptyset}\right) - \frac{c\sqrt{K}}{\nu}u^2 \quad (2)$$

b. In the r-direction

$$v = -\frac{K}{\mu}\left(\frac{\partial P}{\partial r}\right) - \frac{c\sqrt{K}}{\nu}v^2\ldots.. \quad (3)$$

where g is the gravitational acceleration; P, ρ and μ are the pressure, density and dynamic viscosity of the fluid respectively.K and $\emptyset$ is the permeability and porosity of the porous medium respectively where$K = (d^2\emptyset^3)/[150(1-\emptyset)^2]$ and c=$1.75/\left[\sqrt{150}\emptyset^{1.5}\right]$. σ and β_0 are the electrical conductivity of the fluid and the magnetic induction respectively.d is the particle diameter. Differentiate Eq. (2) with respect to r and Eq. (3) with respect to x, then eliminate pressure term from the resulting equations. Invoking the Boussinesq approximation$\rho = \rho_\infty[1 - \beta_T(T - T_\infty) - \beta_C(C - C_\infty)]$, where T and C are temperature and concentration respectively, ρ_∞, T_∞ and C_∞ are the free stream density, temperature, and concentration respectively. β_T and β_C are the thermal and concentration expansion coefficients of the fluid respectively. Under the assumptions that within the boundary layer ($v << u, \partial v/\partial x << \partial u/\partial r$), the final form of the momentum equation will be in the following form

$$-\frac{\mu}{K}\frac{\partial u}{\partial r} - \frac{2c\rho}{\sqrt{K}}u\frac{\partial u}{\partial r} - g\frac{\partial \rho}{\partial r} - \frac{\sigma\beta_0^2}{\emptyset}\frac{\partial u}{\partial r} = 0 \quad (4)$$

2.3 Energy Equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \alpha\left[\frac{\partial 2T}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] + \frac{Q_0}{\rho_\infty c_p}(T - T_\infty) \quad (5)$$

2.4 Mass Conservation Equation

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial r} = \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) \quad (6)$$

where α is the thermal diffusivity and D is the mass diffusivities of the porous medium. $Q_0$is the heat source constant.

2.5 Boundary Conditions

$$r = R \quad v = 0 \quad T = T_w(x) = T_\infty + Ax^n \; C = C_w(x) = C_\infty + Bx^n \quad (7)$$

$$r \to \infty \quad u = U_\infty \quad T = T_\infty \quad C = C_\infty$$

where the subscripts w and ∞ refer to the conditions at the cylinder surface and far from the cylinder surface (free stream) respectively. A, B and n are constants.

2.6 Dimensionless Variables

The following dimensionless variables are introduced to obtain a non-similar equations system that can be applied to the entire regime of mixed convection.

$$\eta = \frac{1}{x}Pe_x^{1/2}\zeta^{-1}\left(\frac{r^2}{2R} - \frac{R}{2}\right)\zeta = \left[1 + \left(\frac{Ra_x}{Pe_x}\right)^{1/2}\right]^{-1} \quad (8)$$

$$f(\zeta,\eta) = \psi(\zeta,\eta)/\left(\alpha R Pe_x^{1/2}\zeta^{-1}\right)\theta(\zeta,\eta) = (T - T_\infty)/(T_w - T_\infty)\,\Phi(\zeta,\eta) = (C - C_\infty)/(C_w - C_\infty) \quad (9)$$

Where η, f, θ and Φ arethe pseudo similarity variable, dimensionless stream function, dimensionless temperature and dimensionless concentration. ψ is the stream function, which is defined by$u = \frac{1}{r}\frac{\partial\psi}{\partial r}$, $v = -\frac{1}{r}\frac{\partial\psi}{\partial x}$such that the continuity equation is automatically satisfied. $Pe_x = U_\infty x/\alpha$ is the local Peclet number.$Ra_x = g\beta_T K x(T_w - T_\infty)/(\alpha\nu)$ is the local Rayleigh number.The parameter ζ is the non-similar mixed-convection parameter such that $\zeta = 0$ for pure free convection and $\zeta = 1$ for pure forced convection. Substituting of Equations (8) and (9) into Equations (4) - (7), the following non-similar dimensionless boundary layer equations will be obtained.

2.7 Dimensionless Momentum Equation

$$[1 + 2If' + M]f'' + (1-\zeta)^2(-\theta' - N\Phi') = 0\ldots.. \quad (10)$$

where

$I = c\sqrt{K}\left(Pe_x^{1/2} + Ra_x^{1/2}\right)^2\alpha/(\nu x)$is the inertia effect parameter, $M = \sigma\beta_0^2 K/(\mu\emptyset)$ is the square of the Hartmann number,

$N = (\beta_C B x^n)/(\beta_T A x^n)$ is the buoyancy ratio.

2.8 Dimensionless Energy Equation

$$-[2\eta\lambda + 1]\theta'' + \left[-\frac{1}{2}\left(1 + n(1-\zeta)\right)f - 2\lambda\right]\theta' + [nf' - Q\zeta^2]\theta = -\frac{n}{2}\zeta(1-\zeta)\left[\frac{\partial f}{\partial\zeta}\theta' - \frac{\partial\theta}{\partial\zeta}f'\right] \quad (11)$$

where $\lambda = \frac{x}{R}\frac{1}{\left(Pe_x^{1/2} + Ra_x^{1/2}\right)}$ is the curvature parameter, $Q = \frac{Q_0 x}{\rho c_p U_\infty}$ is the heat source parameter.

2.9 Dimensionless Mass Conservation Equation

$$-\frac{1}{Le}(2\eta\lambda + 1)\Phi'' + \left[-\frac{1}{2}\left(1 + n(1-\zeta)\right)f - \frac{2}{Le}\lambda\right]\Phi' + nf'\Phi = -\frac{n}{2}\zeta(1-\zeta)\left[\frac{\partial f}{\partial\zeta}\Phi' - \frac{\partial\Phi}{\partial\zeta}f'\right] \quad (12)$$

where $Le = \frac{\alpha}{D}$ is the Lewis number.

2.10 Dimensionless Boundary Conditions

$$f(\zeta,0) = 0\theta(\zeta,0) = 1\,\Phi(\zeta,0) = 1\ldots.. \quad (13)$$

$$f'(\zeta,\infty) = \zeta^2\theta(\zeta,\infty) = 0\,\Phi(\zeta,\infty) = 0\ldots.. \quad (14)$$

Furthermore, physical quantities including velocity components u and v, local Nusselt number Nu_x and local Sherwood number Sh_x, in terms of new variables have the expressions:

$$u = \frac{U_\infty}{\zeta^2}f'v = -\frac{R}{r}\frac{\alpha}{x}Pe_x^{1/2}\frac{1}{\zeta}\left[\frac{1}{2}\left(1 + n(1-\zeta)\right)f - \frac{1}{2}\left(1 - n(1-\zeta)\right)\eta f' - \frac{1}{2}n\zeta(1-\zeta)\frac{\partial f}{\partial\zeta}\right] \quad (15)$$

$$\frac{Nu_x}{Pe_x^{1/2}\zeta^{-1}} = -\theta'(\zeta,0)\,\frac{Sh_x}{Pe_x^{1/2}\zeta^{-1}} = -\Phi'(\zeta,0) \quad (16)$$

The primes in Equations (10)-(16) indicate $\partial/\partial\eta$. The presence of $\partial/\partial\zeta$ in these equations makes them nonsimilar.

3. NUMERICAL METHOD

The domain (ζ, η) is divided into an equal spaced mesh in the ζdirection ($\Delta\zeta = 0.1$) and another equal spaced mesh in the ηdirection ($\Delta\eta = 0.02$).To conserve space, the steps to solve the system of Eqs. (10) to (12) along with the convergence criterion adopted here are presented in reference [12].

4. RESULTS AND DISCUSSIONS

A parametric study is performed for the purpose of study of the effect of all involved physical parameters on the velocity, temperature and concentration profiles as well as local Nusselt and Sherwood numbers. The present results are compared with previously published work on special cases of the problem in order to validate the numerical results to be prepared later. The comparison of local Nusselt number for natural convection for λ values ranged from 0.125 to 5 are shown in Table 1. It is worth noting that zero curvature parameter is refer to as a vertical flat plate case.

Effect of $\boldsymbol{\lambda}$: Increasing the value of curvature parameter from 0.5 to 2 leads to increase velocity, temperature and concentration of the fluid. figure 2a and figure 2b presents the variation of local Nusselt number and local Sherwood number with ζ for different values of. At a given λ value as ζ increases from 0 to 1, the local Nusselt and Sherwood numbers decreases until it reaches a minimum value at certain ζ value, and then increases as ζ goes to 1. This behavior is due to the definition of the local Nusselt and Sherwood numbers and does not indicate that their values for mixed convection is less than for pure natural and forced convection. As λ increase from 0.5 to 2 the curves of local Nusselt and Sherwood numbers increases. This means that a larger value of the curvature parameter leads to a higher heat and mass transfer rates.

Effect of Inertia Parameter *I*: Increasing the value of inertia parameter from 0.1 to 10 has the effect of reducing the velocity of fluid and increase the temperature and concentration of the fluid. It is noticed that for pure forced convection increasing the value of Ido not effect on the temperature and concentration profiles. Figure 3a and figure 3b represents the variation of local Nusselt and Sherwood numbers with ζ for different values of inertia parameter. The local Nusselt and Sherwood numbers decrease as the inertia parameter increases. This is due to the retard of momentum that convey within the boundary layer and consequently reduce the heat and mass transfer. Furthermore, the behavior of the curves implies that the inertia term has little significance in forced convection when the Ergun's correlation is used.

Table 1: Comparison of Local Nusselt Number for Natural Convection for a Vertical Circular Cylinder (Darcy Law, *n*=*N*=*M*=*I*=*Q*=0, *Le*=1)

λ	Present study	Chen &Horng [13]	Kumari et. al. [13]
0.125	0.4929	0.4942	0.4977
0.25	0.5455	0.544	0.5472
0.375	0.5995	0.5939	0.5971
0.5	0.6537	0.6439	0.6479
0.75	0.761	0.7612	0.7509
1	0.8663	0.8669	0.8538
1.25	0.9693	0.9705	0.9562
1.5	1.07	1.0721	1.0576
2	1.2657	1.2703	1.2571
2.5	1.4542	1.4625	1.4519
3	1.6367	1.6498	1.6424
3.5	1.8373	1.833	1.829
4	2.016	2.0126	2.012
4.5	2.181	2.1891	2.1918
5	2.346	2.3673	2.3688

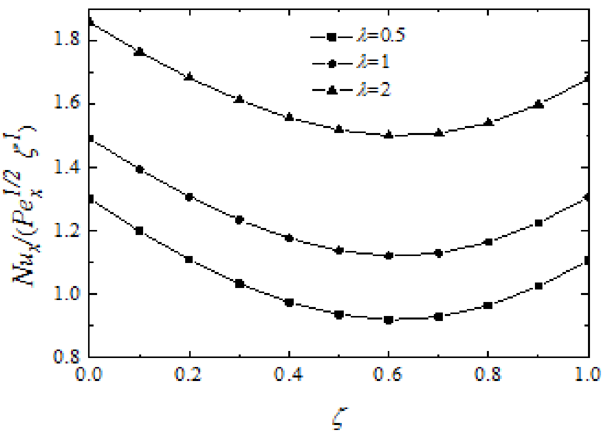

Figure 2a: Variation of local Nusselt Number with λ and ζ ($n = 0.5, N = 2, Le = 5, I = M = Q = 0$).

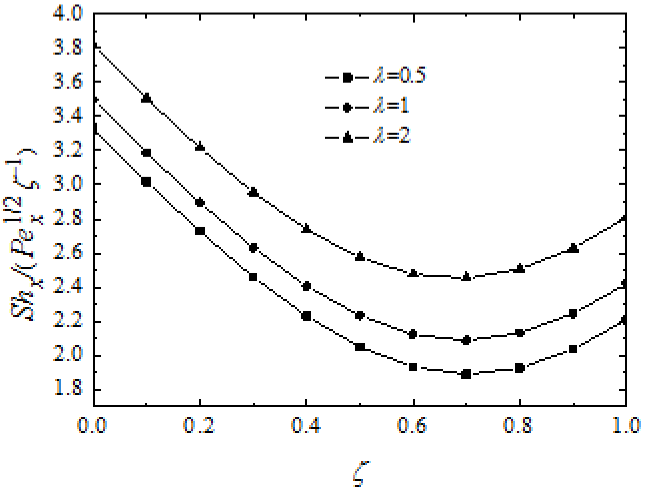

Figure 2b: Variation of Local Sherwod Number with λ and ζ($n = 0.5, N = 2, Le = 5, I = M = Q = 0$).

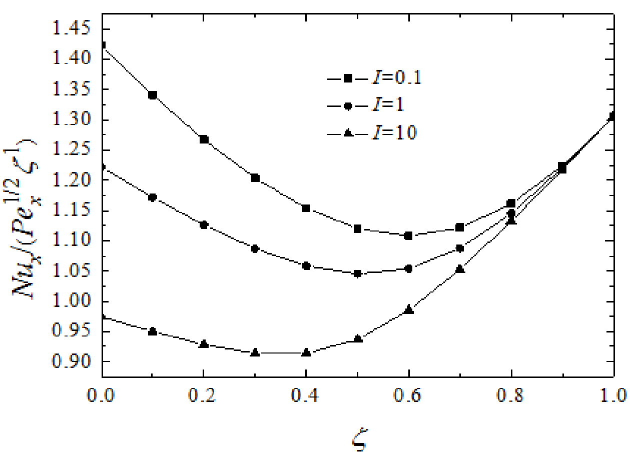

Figure 3a: Variation of Local Nusselt Number with I and ζ ($n = 0.5, N = 2, Le = 5, \lambda = 1, M = Q = 0$).

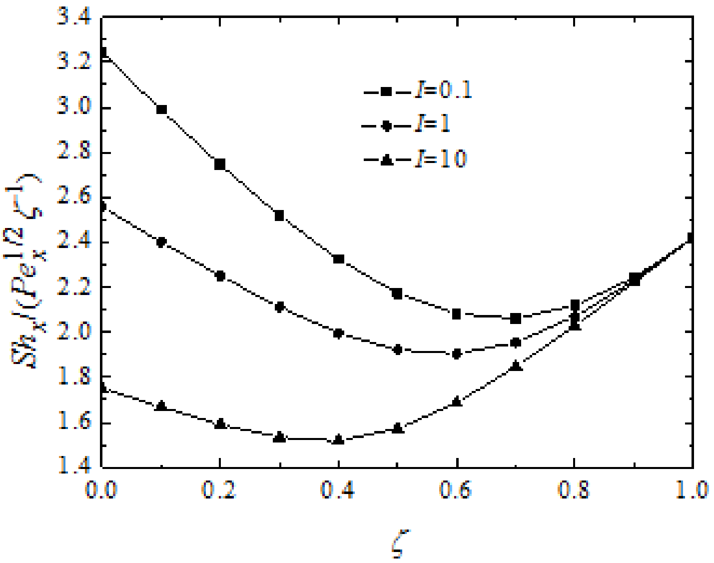

Figure 3b: Variation of Local Sherwod Number with I and ζ (n=0.5,N=2,Le=5,λ=1,M=Q=0).

Effect of *M*: The obtained results showed that increasing of M has the effect of reducing fluid velocity, increasing fluid temperature and concentration. The reduction in flow velocity is due to the resistance of magnetic force named as Lorentz force. This, in turn, reduces the rates of heat and mass transfer which cause increase in the fluid temperature and concentration. The effect of M on local Nusselt and Sherwood numbers are depicted in figure 4a and figure. 4b. It is noticed that for forced convection dominated region the increase in the value of M do not lead to appreciable decrease in the local Nusselt and Sherwood numbers.

Effect of *Le*: It was noticed that the increase in the value of Le from 0.5 to 10, i.e. decrease in the mass diffusivity, leads to decrease in the concentration buoyancy forces (decrease in the concentration of the fluid). This, in turn, decreases the fluid velocity and increases the fluid temperature. Due to the above behavior the local Nusselt number decreases while the local Sherwood number increases as the value of Lewis number increases (see figures. 5a & 5b).

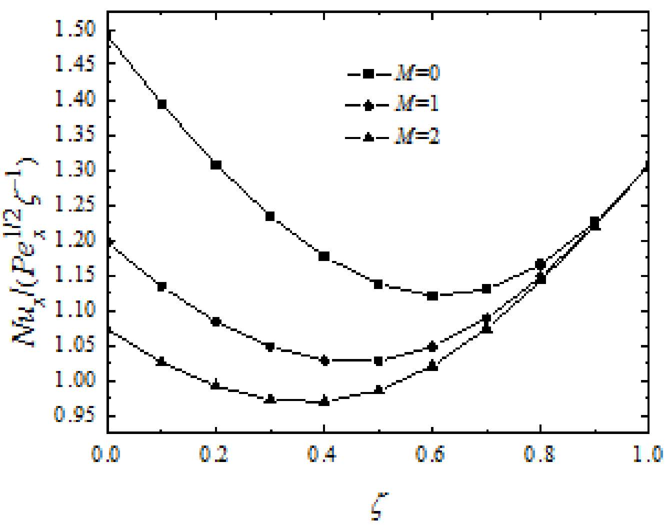

Figure 4a: Variation of Local Nusselt Number with M and ζ (n=0.5,N=2,Le=5,λ=1,I=Q=0).

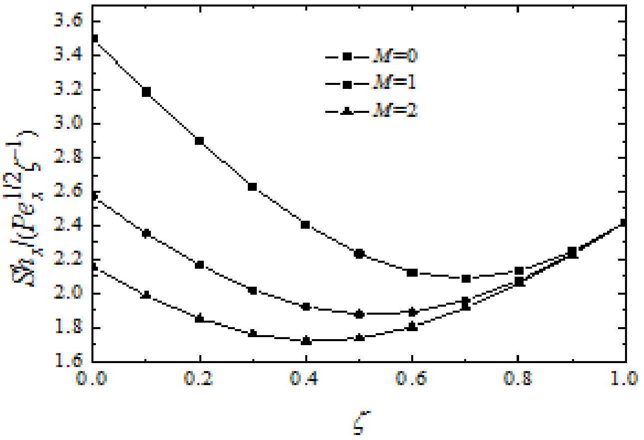

Figure 4b: Variation of Local Sherwod Number with M and ζ (n=0.5,N=2,Le=5,λ=1,I=Q=0).

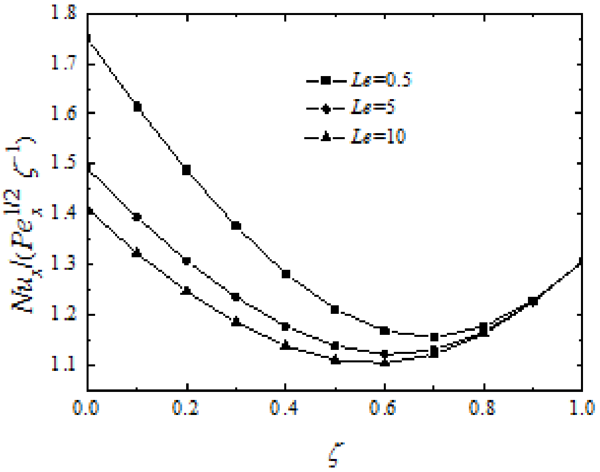

Figure 5a: Variation of local Nusselt Number with Le and ζ (n=0.5,N=2,λ=1,I=M=Q=0).

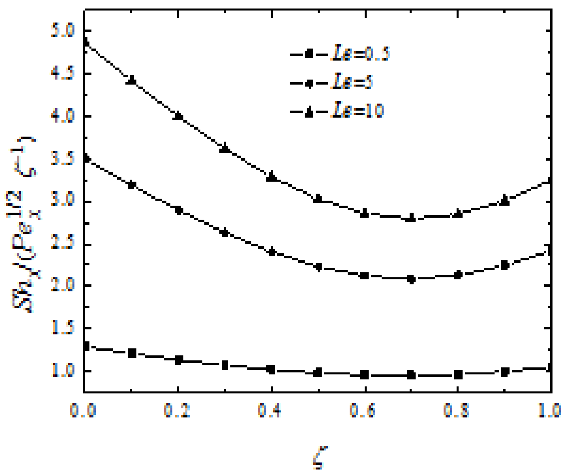

Figure 5b: Variation of Local Sherwod Number with Le and ζ (n=0.5,N=2,λ=1,I=M=Q=0).

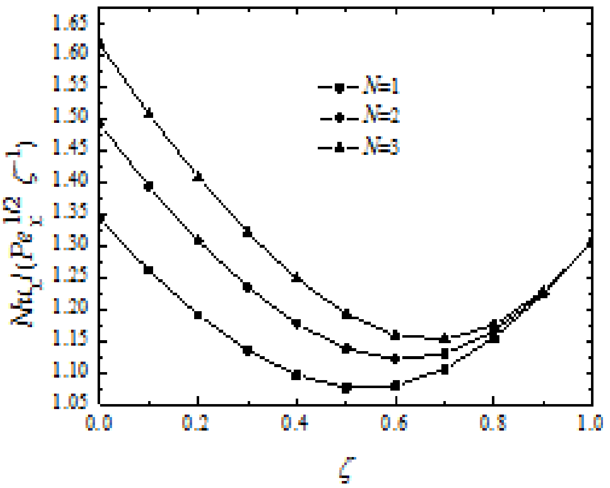

Figure 6a: Variation of Local Nusselt Number with N and ζ ($n = 0.5, Le = 5, \lambda = 1, I = M = Q = 0$).

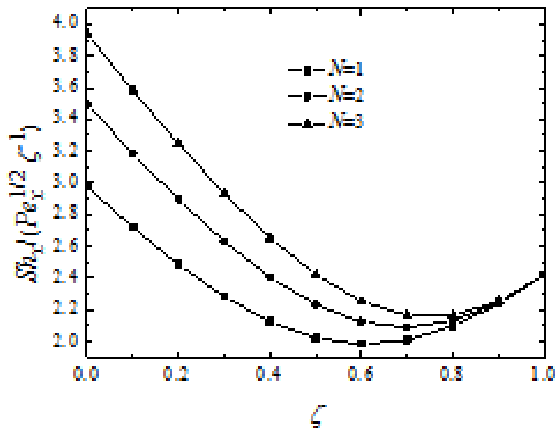

Figure 6b: Variation of Local Sherwod Number with N and ζ ($n = 0.5, Le = 5, \lambda = 1, I = M = Q = 0$).

Effect of N: Increasing the buoyancy ratio parameter from 1 to 3 causes an increase in the fluid velocity near the cylinder surface. The increase in flow velocity will carry more heat and mass from the surface. This cause increase in the temperature and concentration gradients (decrease the thermal and concentration boundary layer thickness). Due to the above reasons it can be seen that from figure 6a and figure 6b as N increases the local Nusselt and Sherwood number increases.

Effect of Q: From the results, increasing the heat generation parameter from 0 to 0.5 doesn't affect the velocity profile for natural convection. For mixed convection, there is a very slight increase (can be neglected) in the velocity of the fluid. Also, the temperature of the fluid doesn't increase for natural convection, but for mixed and forced convection it's increased. This means that as Q increases the thermal boundary layer thickness increases and in turn the value of local Nusselt number decreases as shown in figure 7a. Increasing the value of Q doesn't affect the concentration profiles so that, the local Sherwood number remain approximately at the same value as depicted in figure 7b.

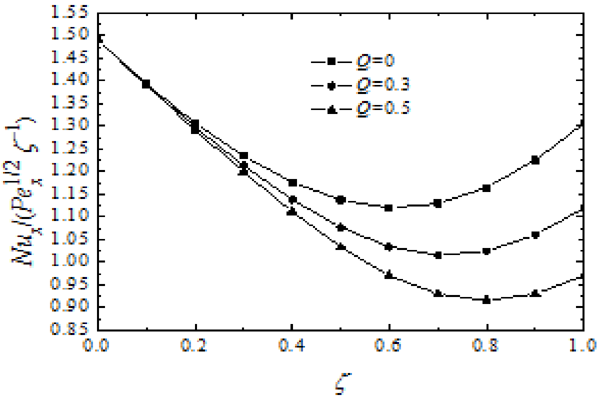

Figure 7a: Variation of Local Nusselt Number with Q and ζ (n=0.5,Le=5,N=2,λ=1,I=M=0).

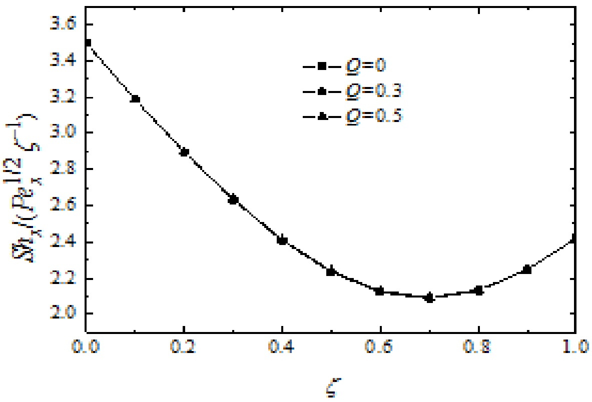

Figure 7b: Variation of Local Sherwod Number with Q and ζ ($n = 0.5, Le = 5, N = 2, \lambda = 1, I = M = 0$).

Effect of Q in the Presence of I and M: As compared to the previous case, similar trends are observed for the effect of heat generation parameter on the profiles under consideration in the presence of I and M in the problem. The exceptions is that reduction in the flow velocity, rising in the temperature and concentration of the fluid, reduction in the local Nusselt number, decreasing in the local Sherwood number when ζ ranging from 0 to 0.5 and increasing when ζ ranging from 0.6 to 1 as shown in figures 8a &8b.

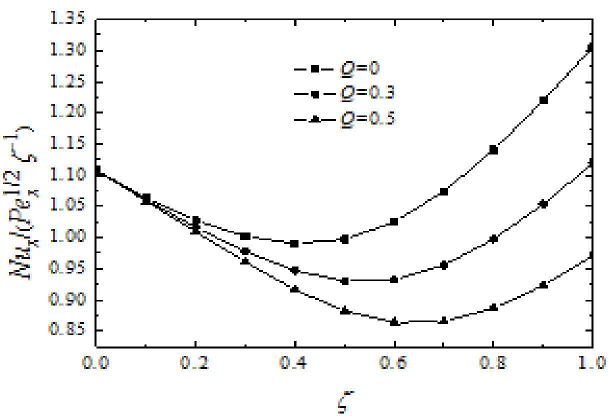

Figure 8a: Variation of local Nusselt number with Q and ζ (n=0.5,Le=5,N=2,λ= I=M=1).

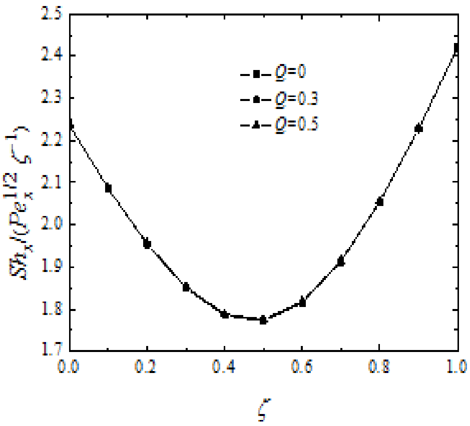

Figure 8b: Variation of Local Sherwod Number with Q and ζ (n=0.5, Le=5,N=2,λ= I=M=1).

5. CONCLUSIONS

From the previous results, it can be concluded that:

- Increasing the values of λ and N leads to increase in the rates of heat and mass transfer.
- The rates of heat and mass transfer decreases as I and M increases.
- As the value of Le increases the rate of heat transfer decreases while the rate of mass transfer increases.
- When the value of Q increases the rate of heat transfer decreases while the rate of mass transfer doesn't affect.

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